SOLIDIFICATION/STABILIZATION OF METALS AND EXPLOSIVES IN SOILS

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ABSTRACT This paper describes two treatability studies for concurrent stabilization/solidification (S/S) of metals and explosives in soils from Open Burning/Open Detonation (OB/OD) activities at an Army site in eastern Oregon. These treatability studies address the destruction and removal efficiencies (DRE), a CERCLA measure of treatment feasibility, and also the ability of the formulations to meet site-specific leachate remediation goals for the treated soils. The untreated site soils exceeded the leachate remediation goals (measured on Toxicity Characteristic Leachate Procedure extracts) for the following compounds: cadmium, lead, Royal Demolition Explosive (RDX), 2,4,6-trinitrotoluene (2,4,6-TNT), and 1,3,5-trinitrobenzene (1,3,5-TNB). Treatability study results indicate that S/S is effective for cadmium and lead by a 30% cement + 10% flyash + 40% soil formulation. However, the explosives compounds, RDX and 2,4,6-TNT, met neither DRE goals nor leachability requirements. Success in removing explosives was achieved by modifying the cement/flyash mixture with an organic binding agent (granular activated carbon) in a slurry with the soil prior to addition of the cement/flyash. The amount of carbon required to achieve the leachate and DRE goals was greater for the more soluble nitramine compounds (e.g., RDX) than for the nitroaromatic compounds (e.g., 2,4,6-TNT). Over the range of tested formulations, all compounds were able to meet the CERCLA guideline of >90% DRE and the site-specific leachability goals. DREs of >99% were achievable for all metals and all explosives by one or another of the formulations tested, except for 1,3,5-TNB, which was not initially highly concentrated in site soils and which reached 90% DRE and met leachability goals. The distribution of 2,4,6-TNT at OB/OD site soils is commonly found to be extremely heterogeneous, possibly due to incomplete combustion during the burning activities. Flecks of solid compound give rise to outlier results during leachate extractions. A compositing technique for sampling and extraction of solidified soils was developed to better represent the average condition of the stabilized soils. The remedial activity will also sift and blend site soils to assure the process meets performance-based leachate goals. Costs for S/S technology application to soils at this site (based on initial contract award costs) are approximately $70/cubic yard, which includes placement in an onsite Army-run landfill. Mix design optimization studies were run subsequent to contract award by OHM Remediation Services, Inc. The study concluded that a mixture of 10% Portland cement + 2.5% activated carbon + 77.5% soil would stabilize soils with explosives in a manner adequate to meet cleanup requirements, taking into account site concentrations and materials handling (screening and blending) prior to S/S. The mix design also tested several other amendments to the cement component, which did not significantly improve performance for explosives above cement/activated carbon. These additions included soluble silicates, ash from rice hulls, and organophilic clays.

KEYWORDS: explosives, metals, stabilization, solidification

INTRODUCTION

Remediations for toxic chemicals occurring in soil as a result of past practices at Department of Defense Open Burning/Open Demolition (OB/OD) sites must commonly deal with co-occurrence of metals and explosives. There are no proven single-step

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technologies for such soils, although a treatment train of incineration followed by stabilization is proven. Bioremediation is not known to be feasible due to the possibility that metals could adversely affect the microbes. A few studies and guidance documents suggest stabilization and solidification may be a viable technology for organic compounds [1-7]. This paper addresses the technical practicability and cost feasibility of the use of stabilization/solidification for explosives and metals at a site in eastern Oregon.

Site

The U.S. Army's Umatilla Chemical Demilitarization Facility (UCDF, formerly the Umatilla Depot Activity) was begun in 1941 as an ordnance depot. Its original mission was handling, storage, renovation, and disposal of conventional ammunition and bombs. In 1962, it began storing containerized chemical agents or munitions. In September, 1994, it was realigned under the Base Realignment and Closure law to remove all conventional munitions. Currently, it is in the process of building an incinerator for the purpose of demilitarizing onsite stored chemical agents, consisting of 11.6% of U.S. chemical munitions supply.

Pertinent site history

An Installation Assessment for UCDF in 1970 disclosed that disposal of process waters from bomb washout into onsite lagoons had contaminated ground water. In 1985, a RCRA Facility Assessment designated 33 Solid Waste Management Units, and subsequently the installation was placed on the National Priorities List. A Federal Facilities Agreement was signed in 1989 among UCDF, EPA, and Oregon Department of Environmental Quality. A Remedial Investigation/Feasibility Study (RI/FS) was initiated consisting of 80 sites. These were grouped into 11 sites, with 9 operable units. Chiefly in this paper we will deal with the remediation requirements for the Ammunition Demolition Area (ADA) operable unit, which was used principally for open burning and free detonation of obsolete explosives including bullets, bombs, mines, and flares.

Alternatives considered

The Superfund ROD [8] for the ADA Operable Unit had three major Remedial Action Components: 1) on-site clearance of unexploded ordnance, 2) solidification/stabilization (S/S) of an estimated 20,000 cubic yards (cy) of metals- and explosives-contaminated soils that were above health-based soil remediation goals, and 3) placement of S/S material in a on-site RCRA subtitle D landfill.

Selection of stabilization/solidification alternative

The Feasibility Study (FS) [9] for the ADA Operable Unit evaluated a number of treatment options. The two primary alternatives were a treatment train of on-site incineration followed by S/S, and S/S treatment directly without the use of incineration. The estimated remediation cost was \$15.7 million (\$480/cy) for the incineration and S/S treatment train, and \$4.8 million (\$147/cy) for the S/S alternative. (For comparison, the actual contract award cost is approximately \$70/cy.) Based on the estimated costs and projected performance efficiency of S/S treatment on metals, semivolatile organics, and non-volatile organics, the direct S/S alternative was selected.

Treatability study

A study was initiated to verify the actual performance of S/S treatment on metals and explosives and to evaluate the need for organic binder in the S/S mix design. A second study is cited in this paper which provides optimization to the feasible remedial solutions found in the treatability study.

In general, remediation literature strongly supports the conclusion that metals and a few organic compounds may be immobilized by stabilization/solidification [1-4]. However, success has not been well documented for soils containing explosives. The soils at the ADA contain nitroaromatic and explosive compounds which necessitated a demonstration of this technology to show its feasibility. This treatability study built on a previous solidification study for lead at another UCDF remediation site which showed that concrete and flyash formulations are effective for immobilizing lead. Subsequent paragraphs describe the performance requirements of the study.

Risk-based performance measures for the treatability study

The ROD stated risk-based soil remediation goals (SRGs) to guide the excavating and treatment of site soils, but it did not completely state the requirements for potential leaching of explosives (leachate remediation goals or SRGs) from the solidified soils. Some of the metals and one explosive constituent (2,4-dinitrotoluene) have RCRA regulatory limits following Toxicity Characteristic Leachate Procedure (TCLP) extraction. For those compounds of concern that did not have regulatory limits, the Army and EPA jointly developed LRGs in a manner consistent with the land disposal restrictions chiefly due to characteristic wastes (40 CFR 261.24, Table 1) and applicable risk-based standards for ground water protection.

Efficiency-based performance measures

EPA established as a guideline in the National Contingency Plan that treatment as part of CERCLA remedies should achieve as a minimum a reduction of 90 to 99 percent in the concentration or mobility for individual contaminants of concern. Treatment technologies or treatment trains that cannot achieve this level of performance on a consistent basis are not sufficiently effective and not deemed appropriate for CERCLA remediations. In order to achieve 90 percent or greater reductions, the systems should be designed to achieve reductions beyond the target level under optimal conditions. The use of DREs was to satisfy the National Contingency Plan guidance. Performance requirements under the contract for the ADA are the same as the risk or regulatorily-driven numbers mentioned in the preceding paragraph.

Site contamination

Contaminants of concern at the ADA include those contaminants that were found in soil in concentrations above background levels determined for that contaminant. Based on this criterion, the compounds in Table 1 were identified as contaminants of concern at the ADA.

Cleanup and treatment goals

Table 2 lists the compounds retained for formulating SRGs and the numeric goals. SRGs assumed a reasonable maximum exposure scenario which considered that future residential use of the ADA is highly unlikely due to the presence of unexploded ordnance in unknown quantities and at unknown depths and locations. For this reason, a future light industrial scenario was selected in the baseline risk assessment.

LRGs are derived as shown in Table 2 in reference to applicable or relevant and appropriate (ARAR) and to-be-considered guidance. In general, either the TCLP regulatory limit was used, or the most conservative ARAR was selected and multiplied by 100 dilution and attenuation factor. This provided a goal that would (paraphrasing the words of 40 CFR subpart 264.342) prevent any release at the landfill that may have an adverse effect on human health or the environment due to migration of waste through soil or in surface water. The primary basis for the LRGs is the long-term protection of ground water. LRGs for the treatability study were established using the following hierarchy:

- TCLP regulatory criteria for several metals and 2,4-dinitrotoluene.
- 100 times the EPA Drinking Water Maximum Contaminant Level.
- 100 times the EPA Lifetime Health Advisories for explosives [11-13].
- 100 times the value in ground water corresponding to 1 x 10^{-6} risk for carcinogens.
- 100 times the value in ground water corresponding to a Hazard Index of 1.0 risk level for non-carcinogens.

METHODS

Soil and initial design selection

Soils were collected at ADA and other UCDF operable units to provide a range of expected site conditions and shipped to U.S. Army Corps of Engineers Waterways Experiment Station (WES) for the initial study, referenced hereafter as the WES study. Selection of cement/fly ash binding and solidification agents was based on a previous treatability study formulation for another UCDF operable unit, the Deactivation Furnace, which had lead-contaminated soils. Chemical and physical testing procedures (such as unconfined compressive strength) are described in

TABLE 1. INITIAL CHEMICALS OF CONCERN AT ADA.

Inorganic Chemicals	Organic Chemicals	Other Chemicals
Aluminum	2,4,5-Trichlorophenoxyacetic Acid	Nitrate/Nitrite
Antimony	Trichloroethylene	Cyanide
Arsenic	Xylenes	
Barium	1,3,5-Trinitrobenzene (TNB)	
Beryllium	2,4,6-Trinitrotoluene (TNT)	
Cadmium	2,4-Dinitrotoluene (DNT)	
Chromium	2,6-Dinitrotoluene (DNT)	
Cobalt	Royal Demolition Explosive (RDX)	
Copper	Tetryl	
Iron	High Melting Explosive (HMX)	
Lead	Nitrobenzene	
Manganese	DDD	
Mercury	DDE	
Nickel	DDT	
Potassium	Dieldrin	
Selenium	Endrin	
Silver	Dichlorprop	
Thallium		
Zinc		

greater detail in a related WES technical publication [10]. Formulations tested included 0.3 cement/0.1 flyash and 0.3 cement/0.3 flyash.

Chemical preparation and analysis methods

SW 846 Method 3050 extraction and Method 6010 were used to extract total metals in soils; the "high level" extraction for soils in SW 846 Method 8330 was used to determine total explosives in soil. The extraction procedure selected for determining leachability of untreated and treated soil was SW 846 Method 1311 (Toxicity Characteristic Leachate Procedure) because the S/S soils would be placed in a former Municipal Solid Waste Landfill.

Activated carbon and other special amendments

The activated carbon, rice hull ash, soluble silicates, and organophilic clays were added for a 5 minute presolidification slurrying step. The mixing of the carbon slurry was performed so that the explosive compound would be adsorbed by the granular activated carbon before the addition of the binders to solidify the material.

Calculation of DREs

Destruction and removal efficiencies were calculated by the following formula:

DRE = (LCus - LCts)/LCus

where **DRE** is Destruction and Removal Efficiency, **LCus** is the leachate

TABLE 2. CLEANUP AND TREATMENT GOALS FOR THE TREATABILITY STUDY OF ADA SOILS.

COMPOUND OF CONCERN	SOIL REMEDIATION GOAL (SRG) (mg/kg)	LEACHATE REMEDIATION GOAL (LRG) by TCLP Extraction (mg/l)	BASIS FOR LRG (see footnotes)
Antimony	820	1.0	100*MCL
Arsenic	15	5	TCLP-RL
Barium	860	100	TCLP-RL
Beryllium	8.1	0.1	100*MCL
Cadmium	28	1	TCLP-RL
Chromium	40	5	TCLP-RL
Lead	500	5	TCLP-RL
Cobalt	25	1,100	100*SDWS
Thallium	160	0.2	100*SDWS
1,3,5-TNB	2.3	0.18	100*RBSL-GW
2,4-DNT	1.9	0.13	TCLP-RL
RDX	52	0.2	100*LHA
2,4,6-TNT	23	0.2	100*LHA
HMX	NAS	40	100*LHA

LHA = EPA Lifetime Health Advisory (Drinking Water)
MCL = Primary National Drinking Water Standard (Maximum Contaminant Level)
RBSCL-GW = EPA Region III published Risk Based Screening Levels for Ground Water Ingestion, June 1995.
TCLP-RL = Toxicity Characteristic Leaching Procedure, Regulatory Limits from 40 CFR 261.24, Table 1
SDWS = Secondary National Drinking Water Standard
NAS = No available standard

concentration (mg/l) in TCLP extracts of the untreated soil, and **LCts** is the leachate concentration (mg/l) in TCLP extracts of treated soil.

In some instances (mainly in the OHM optimization study) there were no LCus values corresponding to the LCts. In this case, linear regression-derived values from total soil concentrations vs. TCLP leachate concentrations were substituted from the WES treatability study.

RESULTS OF WES TREATABILITY STUDY

Results are shown first for untreated and then for treated soils. Treated soils are further broken down into three categories: (a) treated soils using cement/flyash alone for metals and explosives—from the WES study; (b) treated soils using, in addition to the above, granular activated charcoal additions—from the WES study; and (c) treated soils using activated charcoal, soluble silicates, rice hull ash, and organophilic clays—from the OHM Remediation Corporation optimization study [14].

Metals in untreated soils

Although the 9 metals in Table 2 were measured in soils selected for the study, antimony, arsenic, barium, beryllium, cobalt, and thallium were considered to not be exhaustively tested during this study due to their low concentrations in the soils selected for treatment. For these other metals, the Army relied on data from remediation activities at other sites and treatability information from the EPA SITE and RCRA programs that indicate stabilization of the other metals should occur similarly to cadmium and lead. For many of the other metals, S/S is the Best Demonstrated Available Technology [15-19]. Lead and cadmium concentrations were above their SRG values with concentrations of 3,489 and 1,200 mg/kg, respectively. These values were from 90-250% of the 95% upper confidence limits (95% UCLs) on the mean of site concentrations listed in the ROD.

Explosives in untreated soils

Initial soil explosives concentrations for RDX, 2,4,6-TNT, and 1,3,5-TNB were higher than their SRGs and compared favorably with the ROD's listed 95% UCL values for the sites. RDX was present in some ADA soils at 3,000-4,000 mg/kg—about 30 times the site-wise 95% UCL value from the ROD and considerably above the SRG of 52 mg/kg. 2,4,6-TNT was present at an average concentration of 3,800 mg/kg (mean concentration of two subsamples), a higher value than its SRG of 23 mg/kg, although only about 10% of the 95% UCL for this site. 1,3,5-TNB was present at 50 mg/kg compared to its SRG of 2.3 mg/kg.

Metals in treated soils with cement/flyash formulations

Two formulations of 0.3 cement/0.1 fly ash and 0.3 cement/0.3 fly ash met or exceeded the 99% DRE and the LRGs for lead and cadmium for all sites tested.

Explosives in treated soils with cement/flyash formulations

As shown in the second column of Table 3, the explosives 2,4,6-TNT and RDX failed to meet their LRGs. Since the initial RDX concentration of 3,000-4,000 mg/kg was believed to be unrepresentatively high for the site, a "blending" sequence was then tested, using the 0.3 cement/0.1 fly ash formulation. Blends of Site 15 and 19 soils with low-explosive soils derived from within the ADA increased the range for LRG testing for RDX and TNT.

RDX stabilization with 30% cement/10% flyash—WES treatability

Figure 1, plotted on a log-log scale, shows that soils above 30 mg/kg initial RDX soil concentration may not be adequately stabilized. This value of RDX is below the SRG, suggesting that virtually all soil in the field to be excavated may not be stabilized for RDX. Table 3 shows the DRE for RDX, and only a few values were greater than 90%.

TABLE 3. RESULTS OF WES TREATABILITY STUDY. (DREs LESS THAN 90 % ARE SHADED.)

Compound Stabilized by 0.3 Concrete/0.1 Flyash with Carbon Additive Stated	LRG Met at SRG? Y/N	Maximum Soil Value, mg/kg, Stabilized to Meet LRG	Mean DRE	Maximum DRE	Minimum DRE
RDX 0% C	N	30	68.9%	97.7%	<0%[a]
RDX 1% C	Y	~1,800	72.05%	99.97%	44.14%
RDX 5% C	Y	~3,000	99.65%	99.97%	99.33%
RDX 10% C	Y	~3,800	99.74%	99.74%	98.95%
RDX 15% C	Y	>4,000	99.92%	99.97%	99.95%
RDX 20% C	Y	>4,000	99.96%	99.98%	99.95%
TNT 0% C	Y	72	95.5%	99.97%	47.1%
TNT 1% C	Y	>5,000	99.7%	99.97%	99.4%
TNT 5% C	Y	>5,000	99.96%	99.97%	99.96%
TNT 10% C	Y	>5,000	98.01%	99.96%	88.28%
TNT 15% C	Y	>5,000	99.96%	99.96%	99.5%
TNT 20% C	Y	>5,000	99.96%	99.96%	99.95%
HMX 0% C	?[B]	~600[b]	41.2%	81.5%	<0%[a]
HMX 1% C	?[B]	~600[b]	77.1%	99.8%	38.8%
HMX 5% C	?[B]	~600[b]	99.8%	99.8%	99.8%
HMX 10% C	?[B]	~600[b]	99.6%	99.8%	99.1%
TNB 0% C	N	20.1	84.9%[c]	99.998%	<0%[a]
TNB 1% C	Y	>39.5	89.6%[c]	99.96%	45.1%[c]
TNB 5% C	Y	>39.5	98.2%	99.97%	95.2%[c]
TNB 10% C	Y	>39.5	96.2%	99.96%	88.3%[c]

[a]Due to sample variation, some replicates leached more in the stabilized than in the untreated soils.
[b]The leachate from the highest bulk soil concentration tested did not exceed the LRG even without stabilization.
[c]These low DREs are due, in part, to a low initial concentration in the soils.

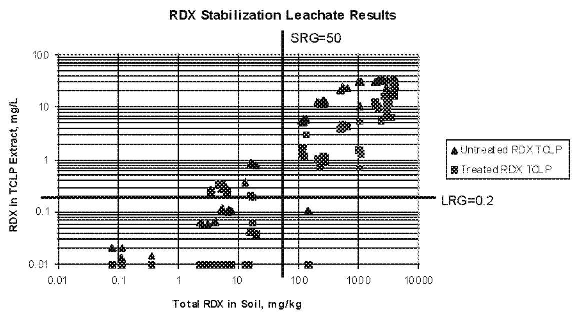


FIGURE 1. RDX LEACHATE RESULTS FROM INITIAL SOILS AND FROM TREATED AND UNTREATED SOILS (CEMENT/FLYASH ONLY).

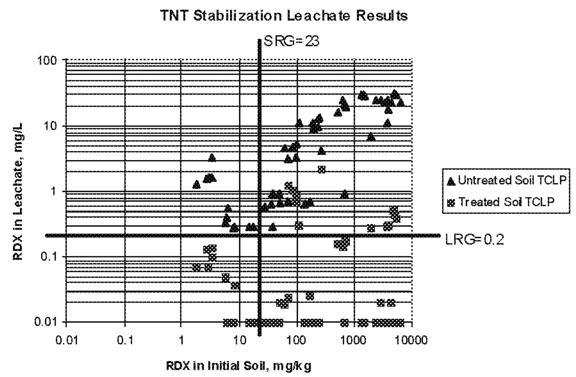


FIGURE 2. TNT LEACHATE RESULTS FROM INITIAL SOILS AND FROM TREATED AND UNTREATED SOILS (CEMENT/FLYASH ONLY).

2,4,6-TNT stabilization with 30% cement/10% flyash

Figure 2 shows that TNT leachate from stabilized and solidified soils was less problematic than RDX, but there were numerous failures of the LRG. Initial soil concentrations above the SRG and above the LRG occurred in 12 cases out of 38 in the testing. DREs for TNT are shown in Table 3. While many samples were in the 90th percentile, there were numerous failures. There was one experimental instance where a bulk soil concentration of TNT as low as 72 mg/kg failed by other instances of considerably higher initial values such as 6,000 mg/kg that were adequately treated to meet the LRG. These

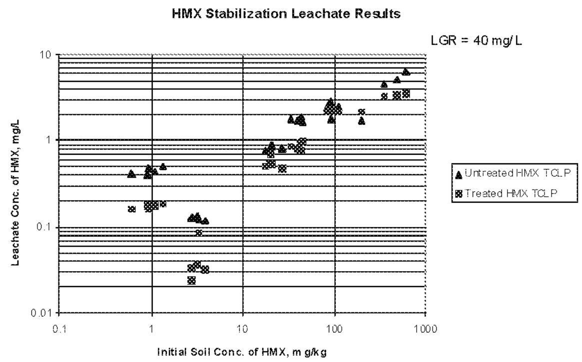


FIGURE 3. HMX LEACHATE RESULTS FROM INITIAL SOILS AND FROM TREATED AND UNTREATED SOILS (CEMENT/FLYASH ONLY).

peculiar results may be due to inclusion of small pieces of TNT in the portion solidified; in other words, it may be due to sample heterogeneity which was not represented by the total TNT determination.

HMX stabilization with 30% cement/10% flyash

Figure 3 displays HMX stabilization without carbon addition. All trials (including the untreated soils) passed the leachability treatment standard of 40 mg/l. DREs for HMX are shown in Table 3. While they do not meet the 90% requirement, the initial concentrations probably adversely affect this.

1,3,5-TNB stabilization with 30% cement/10% flyash

The concrete/fly ash formulation did not meet the 99% DRE (Table 3). Figure 4 shows the disposition of TNB (detected values only) in the initial leachate study without carbon additions. It is apparent that TNB at considerably above the SRG may fail the low LRG for this compound.

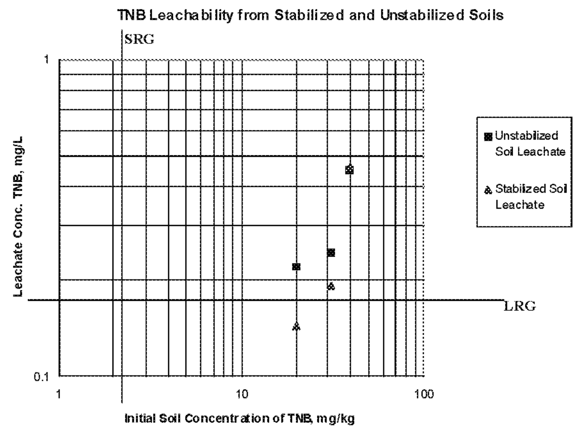


FIGURE 4. TNB LEACHATE RESULTS FROM INITIAL SOILS AND FROM TREATED AND UNTREATED SOILS (CEMENT/FLYASH ONLY).

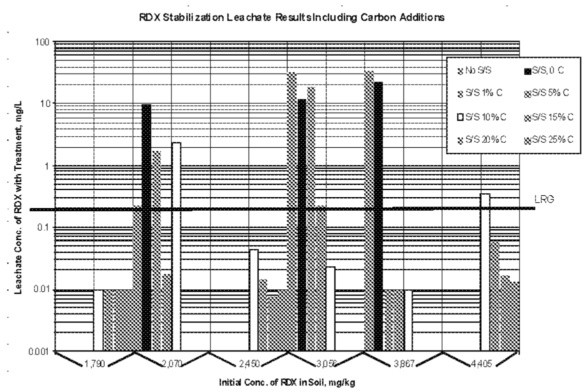


FIGURE 5. RDX LEACHATE RESULTS FROM TREATED AND UNTREATED SOILS WITH AND WITHOUT CARBON ADDITION.

RDX with carbon additions to 30% cement/10% flyash

Figure 5 shows the results of trials for RDX (average initial and leachate replicate samples depicted). The LRG was met with 5% carbon addition, and there was greater efficacy at higher concentrations. As for DRE, all formulations at or above 5% carbon met the required 99% DRE. Formulations with 15% carbon and above reliably met a high, 99.9% DRE.

It is apparent that activated carbon slurry treatment before S/S has utility in stabilizing

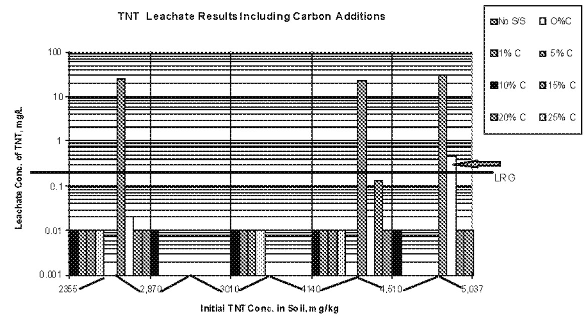


FIGURE 6. TNT LEACHATE RESULTS FROM TREATED AND UNTREATED SOILS WITH AND WITHOUT CARBON ADDITION.

RDX even at high concentrations. Ten percent carbon is more effective than 1%, but both have occasional failures. No trial failed the LRG for the 15% formulation. It is concluded that stabilization for RDX is feasible with most onsite soils after both blending and granular activated charcoal amendment. Note that these experimental values are considerably above Site 15-B soils analyzed after the RI, of which the maximum was 433 mg/kg. While soils up to 4,000 mg/kg could locally exist (and in this case, probably originating from a burn sludge), the mean RDX concentration at the site is probably considerably lower.

2,4,6-TNT stabilization with carbon additions to 30% cement/10% flyash

The LRG for TNT was met using the stabilization formulations with granular activated charcoal. Table 3 shows DREs. All carbon formulations except 10% carbon met the 90% requirement, and 5%, 15%, and 20% results exceeded 99.9% DRE. The 10% result may be due to inhomogeneity of TNT in the S/S soil. In Figure 6, TNT leaching results are shown over a range of concentrations for unstabilized, stabilized without activated carbon addition, and stabilized samples with activated carbon additions. No treatment formulation with

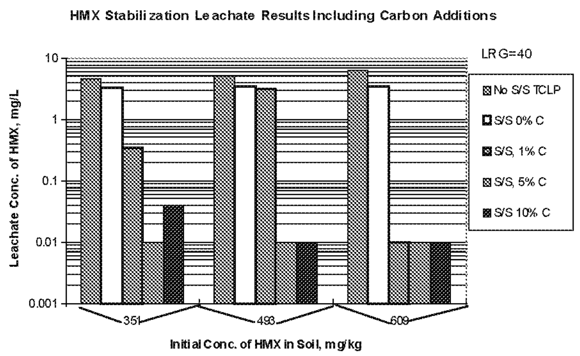


FIGURE 7. HMX LEACHATE RESULTS FROM TREATED AND UNTREATED SOILS WITH AND WITHOUT CARBON ADDITION.

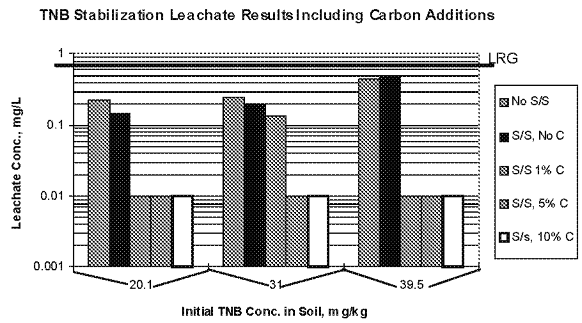


FIGURE 8. TNB LEACHATE RESULTS FROM TREATED AND UNTREATED SOILS WITH AND WITHOUT CARBON ADDITION.

carbon failed the treatment standard, although one treatment failed it without carbon.

HMX stabilization with carbon additions to 30% cement/10% flyash

Although HMX was not initially present at a level that would cause failure of the LRG as seen in Figure 7, it is possible to calculate a DRE for it. Addition of 5% and 10% carbon exceeded 99% DRE.

1,3,5-TNB stabilization with carbon additions to 30% cement/10% flyash

Neither unstabilized nor stabilized soils without carbon additions failed the LRGs. For 5% carbon addition and above, TNB was not detected in the leachate (the values shown are ½ the quantitation limit). The 99% DRE was not met for any average performances of the leachate test. This may be an artifact of the low values that were tested. Figure 8 presents the stabilization results for TNB.

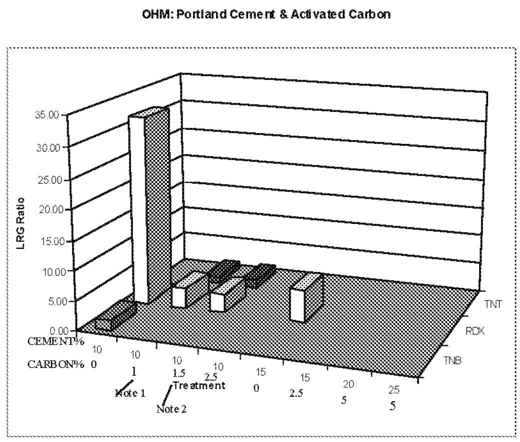
RESULTS OF OHM REMEDIATION CORPORATION BENCH SCALE OPTIMIZATION STUDY

Availability of data and report

The results of this testing are available in an appendix to a final Remedial Action Management Plan [21]. A full-scale demonstration of the methods and mixtures described following as "final" mix designs will occur in midsummer, 1996.

Differences in initial soils between studies

Maximum initial soil concentrations of explosives in soils selected by OHM were generally lower than those used in the WES study. This condition is likely to better reflect the actual condition of site soils after unexploded ordnance clearing, grading, sizing, and mixing of the soils occurs prior to introduction of the soil into the pugmill for S/S. Lead, at 1,400 mg/kg, was approximately 41% of the maximum WES study value; cadmium, at 83 mg/kg, was 7% of WES' maximum; RDX, at 600 mg/kg, was approximately 15% of WES' value; TNT, at 900 mg/kg, was approximately 24%



Note 1: RDX results shown are an average of 3 replicate analyses from one block
Note 2: TNT results shown are the worst of 3 replicate analyses from one block (see discussion in text of TNT variability)

FIGURE 9. LEACHATE RESULTS FROM TREATED SOILS WITH AND WITHOUT CARBON ADDITION. (NOTE: LRG RATIOS LESS THAN 1.0 ARE NOT DISPLAYED.)

of WES' value; and TNB, at 51 mg/kg, was essentially the same as WES' value.

DREs were approximated for the OHM study by using regressions on TCLP metals and explosives from untreated soils versus bulk concentrations from the WES study. In Table 4, one-half of the quantitation limit was used to replace nondetected values.

Differences in mix designs

WES' mixture was about 40% soil by weight, with 40% solid amendments, whereas OHM's mix designs include up to 82% soil and 11% solid amendments. The final OHM mix designs do not include flyash. The period of curing for the final blocks generally required longer (7 days vs. 2 days in the WES study) to meet the unconfined compressive strength performance requirement of 50 pounds per square inch, and often to meet the LRG. As seen from Table 4, there is an apparent improvement in the unconfined compressive strength of the stabilized soils with the addition of the carbon to 2.5%. Also, the WES treatability study was usually run in triplicate; with the exception of the final run to confirm the "final mix design," the OHM study was unreplicated. The final run was run in triplicate samples from the same blocks.

Leachate results for metals

Metals results (which are not shown here) showed efficient stabilization at an 8% cement/87% soil/5% water mixture.

Leachate results for explosives with cement/carbon combinations

Figure 9 displays the cement/activated carbon testing that was accomplished. The Y axis is "LRG Ratio," that is, the leachate concentration normalized to the LRG. For compounds that appear above 1, the LRG

TABLE 4. ESTIMATED DREs FOR THE FINAL MIXTURES OF THE OHM STUDY AND RELATED UNCONFINED COMPRESSIVE STRENGTHS.

% Soil	% Cement	% GAC	Cadmium DRE	Lead DRE	TNT DRE	RDX DRE	TNB DRE	UCS[a] (psi)
79	8	0	99.6	99.8	NA	NA	NA	86.1
82	10	1.0	98.6	99.9	~90	<90	~97	60.9
78.5	10	1.5	98.6	99.9	~97	~92	~98	81.2
77.5	10	2.5	98.6	99.9	>99	>99	~98	117

[a]UCS = unconfined compressive strength in pounds per square inch

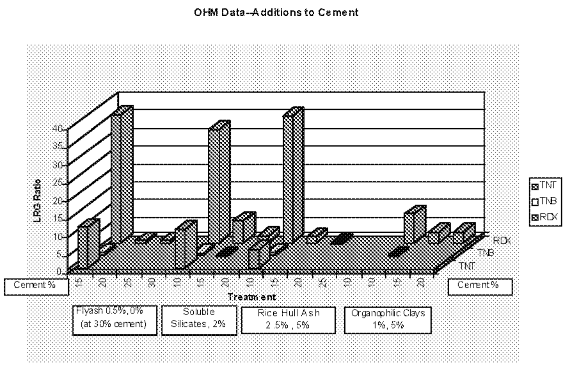


FIGURE 10. LEACHATE RESULTS FROM TREATED AND UNTREATED SOILS WITH OTHER ADDITIONS THAN GRANULAR ACTIVATED CARBON. (NOTE: LRG RATIOS LESS THAN 1.0 ARE NOT DISPLAYED.)

was exceeded. (For simplicity, this and the following chart have been modified not to show LRG ratios between 0 and 1.) The optimized mix design was 10% cement + 2.5% activated carbon + 77.5% soil + 10% water based on the lowest concentration of cement and carbon that achieved the LRG.

Leachate results for other amendments

OHM determined to try other amendments to test their relative efficacy to stabilize explosives, and conducted these studies before the final selection of a mix design. Figure 10 shows results for flyash, soluble silicates, ash from rice hulls, and organophilic clays. Comparable results to the no carbon addition trial from Figure 9 are seen in the flyash samples; at higher concentrations, it appears that there is no significant improvement over carbon additions. A similar pattern appears for soluble silicates. Rice hull ash appears to behave as an inefficient binder compared to comparable levels of activated charcoal. The only trial that passed all LRGs had a rich cement mixture (25%) along with a rich hull ash mixture (5%). This was not considered cost effective. Organophilic clays appear to lower RDX solubilities compared to concrete alone and concrete plus flyash; but not enough to pass LRGs.

CONCLUSIONS AND RECOMMENDATIONS

Metals

Both studies indicated S/S has substantial success relative to the LRGs for lead and cadmium, although soils selected dictated that other metals were not tested definitively. The treatability study results do not indicate significant matrix effects for the cadmium or lead that could lead to difficulties with immobilizing other metals. Accordingly, it is concluded that the S/S formulations and soil contaminant concentrations evaluated would be successful in stabilizing all the metals of concern at the ADA.

RDX

RDX and other nitramines have significant leaching potential, which is significantly reduced by carbon additions such that DRE and LRG standards are met. The carbon preslurrying step has been confirmed by two research groups to be effective for this compound. Although RDX was not generally a "hot spot" chemical (the soils used in the WES study were unusually high due to a biased collection of burned waste pile soils), there appears to be added efficacy from the blending during materials handling which should assist in achieving reliably stabilized products.

2,4,6-TNT

The data indicate concrete/fly ash/carbon formulations that reliably stabilize TNT to meet the LRG and DRE standards. However, based on review of replicate samples from the same solidified block, it appears that flecks of explosive in the 2 gram subsample of the pretreated soil used for the Method 8330 analysis, or the 100 gram sample of the soil extracted during the TCLP, can have a significant random adverse impact on the representativeness of the results to characterize the S/S sample. This may be seen in the WES results in Figure 6 (see arrow at right side of chart), and the OHM data in Figure 9 (see notes indicated at bottom of chart). Accordingly, a sampling procedure was proposed for the contracted remediation to avert misinterpretations of unrepresentative analyses:

I. Five subsamples will be taken and each subjected to the TCLP extraction procedure.
II. An aliquot of each subsample will be added to make a composite analytical sample.
III. The remaining subsample extracts will be archived in the dark at 4°C until the results from the initial 8330 analyses are available.
IV. If the composite sample result(s) exceed the LRG, the resulting block will be counted as a preliminary failure, and the 5 archived extracts will then be subjected to individual analysis. If the analysis has exceeded holding time, the blocks must be re-extracted for TCLP.
V. If the second analysis shows a subsample is causing the apparent failure, the following "counting rules" will be used:
    1. The average concentration of the solidified/stabilized material will be calculated without the subsample—if the high subsample is greater than the 95% upper confidence limit on the mean of the other subsamples, the high one will be considered an outlier, and the mean of the remaining samples will determine whether the treatment batch has passed the leachate requirements.
    2. If the subsample is not seen to be an outlier, then the treatment batch represented by the block must be broken up, crushed, and resolidified until it passes the requirements.

HMX

HMX at the concentrations seen in these studies is not likely to fail the LRGs even without carbon additions. Carbon formulations improved the DRE from 90 to 99%.

1,3,5-TNB

TNB was effectively stabilized by carbon-containing formulations and met the 90% DRE marginally, possibly due to low initial concentrations. 1,3,5-TNB's SRG is also at a relatively low soil concentration, 2.3 mg, and the LRG is also lower than other explosives except for 2,4-DNT, 0.18 mg/l. Anticipating possibly higher hot spots of this compound, it is recommended that it is prudent to use carbon additions and to blend TNB-containing soil prior to solidification. This is planned during the remediation activity.

Cost effectiveness

At around $70 per cy treated, S/S technology is considerably cheaper than bioremediation (windrow composting at the same installation cost approximately $350/cy). Likewise, it is much cheaper than incineration followed by S/S: estimated costs that would meet the RCRA combustion strategy is $1,600-$2,500 per cy for this treatment train.

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REFERENCES

1. E. Bates, Applications Analysis Report: Silicate Technology Corporation's Solidification/Stabilization Technology for Organic and Inorganic Contaminants in Soils, EPA-68-03-3484, EPA-68-CO-0047, EPA/540/AR-92/010, PRC Environmental Management, Inc., McLean, VA., Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Lab, 1992.

2. E.R. Bates, P. Dean, and E. Klich, Chemical Stabilization of Mixed Organic and Metal Compounds, EPA SITE Program Demonstration of the Silicate Technology Corporation Process, EPA/600/J-92/403, Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Lab, 1992.

3. R.J. Turner and M.B. Foerst, Management of Arsenical Wood Preserving Residuals by Recovery and Immobilization, EPA-68-C9-0036, EPA/600/A-93/160, IT Corp., Cincinnati, OH, Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Lab, 1993.

4. U.S. EPA, Engineering Bulletin: Solidification/Stabilization of Organics and Inorganics, EPA/540/S-92/015, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH, May 1993.

5. U.S. EPA, Center for Environmental Research Information, Solidification/Stabilization of Organic/Inorganic Contaminants, EPA/540/MR-92/010, 1992.

6. U.S. EPA, Handbook for Stabilization/Solidification of Hazardous Wastes, EPA/540/2-86-/001, Office of Research and Development, Cincinnati, OH, 1986.

7. U.S. EPA, Technical Resource Document: Solidification/Stabilization and its Application to Waste Materials, EPA/530/R-93/012, Office of Research and Development, Washington, DC, July 1995.

8. U.S Army, U.S. EPA Region 10, and Oregon Department of Environmental Quality, Final Record of Decision, Umatilla Depot Activity, Ammunition Demolition Activity Area Operable Unit, June 10, 1994.

9. U.S. Army Environmental Center, Final Feasibility Study for Ammunition Demolition Activity Area (OU4) at the Umatilla Army Depot Activity, U.S. Army Environmental Center Report No. ENAEC-BC-CR-93112, November 15, 1993.

10. M. Channel, Solidification/Stabilization of Metals and Explosives in Soils, U.S. Army Corps of Engineers, Waterways Experiment Station (WES), Vicksburg, MS, WES Technical Report EL-96-4, 1996.

11. U.S. EPA, Trinitrotoluene Health Advisory, Office of Drinking Water, Washington, DC, January 1989.

12. U.S. EPA, Health Advisory for Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), Criteria and Standards Division, Office of Drinking Water, Washington, DC, November 1988.

13. U.S. EPA, Health Advisory for Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), Criteria and Standards Division, Office of Drinking Water, Washington, DC, November 1988.

14. OHM Remediation Services Corporation, Final Phase II Remedial Action Management Plan for Contaminated Soil Remediation at the Ammunition Demolition Area, Former Deactivation Furnace, and Miscellaneous Sites, Umatilla Depot, Hermiston Oregon, Appendix D (Treatability Study), Prepared for the U.S. Army Corps of Engineers, 1996.

15. L. Rosengrant and J. Labiosa, Final Best Demonstrated Available Technology (BDAT) Background Document for Chromium Wastes D007 and U032, vol. 22, EPA-68-W9-0068, EPA/530/SW-90/059V, Versar, Inc., Springfield, VA, Environmental Protection Agency, Washington, DC, Office of Solid Waste, 1990.

16. L. Rosengrant and R. Craig, Final Response to BDAT Related Comments Document, F025, K002-K008, K011, K013-15, K046, K061, K069, vol. 1-K, EPA/530/SW-90/061M, Environmental Protection Agency, Washington, DC, Office of Solid Waste, 1990.

17. L. Rosengrant and R.M. Craig, Final Best Demonstrated Available Technology (BDAT) Background Document for P and U Thallium Wastes, vol. 18, EPA-68-W9-0068, EPA/530/SW-90/059R, Versar, Inc., Springfield, VA, Environmental Protection Agency, Washington, DC, Office of Solid Waste, 1990.

18. L. Rosengrant and R. Craig, Final Response to BDAT Related Comments Document, D009, K044, K045, K047, D011, P119, P120, and P and U Wastes, vol. 1-I. EPA/530/SW-90/061K, EPA-68-W9-0068, Environmental Protection Agency, Washington, DC, Office of Solid Waste, Versar, Inc., Springfield, VA, 1990.

19. L. Rosengrant and R.M. Craig, Final Best Demonstrated Available Technology (BDAT) Background Document for Barium Wastes (D005 and P013), vol. 20, EPA-68-W9-0068, EPA/530/SW-90/059T, Versar, Inc., Springfield, VA, Environmental Protection Agency, Washington, DC, Office of Solid Waste, 1990.

20. K.Y. Cheng and P.L. Bishop, Sorption, Important in Stabilized/Solidified Waste Forms, EPA/600/J-94/140, Dames and Moore, Cincinnati, OH, Cincinnati Univ., OH Dept. of Civil and Environmental Engineering, Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Lab, 1994.

21. K.Y. Cheng and P.L. Bishop, Metals Distribution in Solidified/Stabilized

Waste Forms After Leaching, EPA-R-816700, EPA/600/J-94/139, Dames and Moore, Cincinnati, OH, Cincinnati Univ., OH Dept. of Civil and Environmental Engineering, Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Lab, 1994.